

H. G. Stratmann

# Using Medicine in Science Fiction

The SF Writer's Guide  
to Human Biology



Springer

## Science and Fiction

### *Editorial Board*

Mark Alpert  
Philip Ball  
Gregory Benford  
Michael Brotherton  
Victor Callaghan  
Amnon H Eden  
Nick Kanas  
Geoffrey Landis  
Rudi Rucker  
Dirk Schulze-Makuch  
Rüdiger Vaas  
Ulrich Walter  
Stephen Webb

## Science and Fiction – A Springer Series

This collection of entertaining and thought-provoking books will appeal equally to science buffs, scientists and science-fiction fans. It was born out of the recognition that scientific discovery and the creation of plausible fictional scenarios are often two sides of the same coin. Each relies on an understanding of the way the world works, coupled with the imaginative ability to invent new or alternative explanations - and even other worlds. Authored by practicing scientists as well as writers of hard science fiction, these books explore and exploit the borderlands between accepted science and its fictional counterpart. Uncovering mutual influences, promoting fruitful interaction, narrating and analyzing fictional scenarios, together they serve as a reaction vessel for inspired new ideas in science, technology, and beyond.

Whether fiction, fact, or forever undecidable: the Springer Series “Science and Fiction” intends to go where no one has gone before!

Its largely non-technical books take several different approaches. Journey with their authors as they

- Indulge in science speculation – describing intriguing, plausible yet unproven ideas;
- Exploit science fiction for educational purposes and as a means of promoting critical thinking;
- Explore the interplay of science and science fiction – throughout the history of the genre and looking ahead;
- Delve into related topics including, but not limited to: science as a creative process, the limits of science, interplay of literature and knowledge;
- Tell fictional short stories built around well-defined scientific ideas, with a supplement summarizing the science underlying the plot.

Readers can look forward to a broad range of topics, as intriguing as they are important. Here just a few by way of illustration:

- Time travel, superluminal travel, wormholes, teleportation
- Extraterrestrial intelligence and alien civilizations
- Artificial intelligence, planetary brains, the universe as a computer, simulated worlds
- Non-anthropocentric viewpoints
- Synthetic biology, genetic engineering, developing nanotechnologies
- Eco/infrastructure/meteorite-impact disaster scenarios
- Future scenarios, transhumanism, posthumanism, intelligence explosion
- Virtual worlds, cyberspace dramas
- Consciousness and mind manipulation

H. G. Stratmann

# Using Medicine in Science Fiction

The SF Writer's Guide to Human Biology

 Springer

H. G. Stratmann  
Springfield  
Missouri  
USA

ISSN 2197-1188

ISBN 978-3-319-16014-6

DOI 10.1007/978-3-319-16015-3

ISSN 2197-1196 (electronic)

ISBN 978-3-319-16015-3 (eBook)

Library of Congress Control Number: 2015940326

Springer Cham Heidelberg New York Dordrecht London

© Springer International Publishing Switzerland 2016

The publisher, the authors and the editors are safe to assume that the advice and information in this book are believed to be true and accurate at the date of publication. Neither the publisher nor the authors or the editors give a warranty, express or implied, with respect to the material contained herein or for any errors or omissions that may have been made.

This work is subject to copyright. All rights are reserved by the Publisher, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilms or in any other physical way, and transmission or information storage and retrieval, electronic adaptation, computer software, or by similar or dissimilar methodology now known or hereafter developed.

The use of general descriptive names, registered names, trademarks, service marks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.

Printed on acid-free paper

Springer International Publishing is part of Springer Science+Business Media ([www.springer.com](http://www.springer.com))

*To my wife, Dr. Maryellen Amato, and our sons, Henry III and Joseph. You have enriched my life beyond measure.*

# Preface

Over the past two decades I have given talks and been on panels dealing with space medicine, suspended animation, medical nanotechnology, and similar topics at science fiction conventions. Audience members have often asked me where they could read more about these subjects that blend medicine with science fiction. Until now I could only tell them that information is scattered over numerous books, research papers, and other sources, with many of them written at a technical level not geared for a general readership. Some of those individuals have urged me to write a book covering those topics.

*Using Medicine in Science Fiction* is my response to that request. Its purpose is to describe how the human body actually works, the myriad ways that space travel, radiation exposure, and other factors affect it, and the biological challenges to modifying and “improving” it. Science fiction writers can use this information to make their depictions of human biology more accurate and plausible. Readers will gain a better understanding of the medical science underlying such commonly used plot elements as life extension, cloning, genetic engineering, and bionics.

The subjects I cover in this book are complex and vast. No single work can comprehensively include what is currently known about them, and new research will further expand our knowledge and capabilities. Instead each chapter focuses on presenting core concepts about human biology and medical care, summarizing the current status of individual topics (e.g. stem cells and organ transplantation), and describing what would need to be done to turn ideas now solely the provenance of science fiction into reality.

Science fiction does not need to be ultrarealistic in its portrayals of medical issues to be effective, enjoyable, and thought-provoking as fiction. Sometimes a little “blurring” of medical detail is, in fact, justified by the greater goal of making a story, television show, or movie succeed as a whole. A science fiction work can still triumph as an exercise in imagination, entertainment, and/or exploration of the human condition even if the medicine in it stretches plausibility to or beyond its breaking point.

But there is a danger with putting the priorities of fiction over those of science. A work depicting suspended animation, advanced genetic engineering,

or other medical elements well beyond current capabilities may give those unfamiliar with real medicine an erroneous impression of how “easy,” plausible, or even possible they are. This can do a disservice by inadvertently “teaching” its audience something that might be dubious at best or perhaps simply wrong.

While I hope you find the information in this book interesting and enlightening in its own right, it is also meant to serve another very important purpose. It will give you a better appreciation for how much of a difference there is between current medical science and that shown in science fiction. Sometimes the gap between them is small and might be bridged in the near future. In other cases there is a huge chasm that will require overcoming tremendous challenges, with no guarantee that they can be actually be done at all or at least used in a practical way. And it will also help you identify what medicine is “impossible” so that you can, if you choose, decide to suspend your disbelief to enjoy a science fiction work rather than learn something that is actually not correct.

In medicine as in life, it is best for each of us to know what is actually true. The second best thing, as Socrates knew, is to know that we really do not know something with certainty, and to try our best to understand and learn it. By far the worst situation is to “know” something is true when it really is not, or is at least less certain to be right or more complex than we think. Similarly, medical science must also continuously reevaluate what it “knows” based on new discoveries, facts, and concepts.

This book gives a snapshot of where many medical concepts used in science fiction are right now in their development. However, even the most informed speculation on when or whether they will eventually become real has an unavoidably wide margin of uncertainty. Fortunately, whatever path the future of medicine does take, we have science fiction to help imagine what it might be.

# Acknowledgments

The best thing about becoming a science fiction writer is that it has brought me into contact with so many fine, accomplished individuals in the field. This book would not have been possible without their inspiration, example, and help.

Two people in particular deserve special thanks. The first, Gerald (G. David) Nordley, is an aeronautical engineer and creator of superb, scientifically accurate science fiction. Gerald offered me the opportunity to be his coauthor on a futuristic story with a medical theme. His proposal made me wonder for the first time whether I had the ability to go from just reading science fiction to actually writing it. Our collaboration (and my first sale!), “Tin Angel,” was published in the July 1994 issue of *Analog Science Fiction and Fact*. Everything I have accomplished in the field since then I ultimately owe to Gerald, for which he has my undying gratitude.

The second person is Dr. Stanley Schmidt, who recently retired as editor of *Analog* after over three decades in that position. Encouraged by the success of “Tin Angel,” I began submitting my own stories to *Analog* in the mid-1990s. Despite the many failings and weaknesses of those early efforts, Stan patiently encouraged me to keep trying and suggested ways to improve my writing. The fact that I was eventually able to meet the high standard of quality he set at *Analog* and sell so many stories and science fact articles to him is a testament to his incomparable abilities as an editor and mentor. Anyone who has ever met and worked with Stan cannot help but be impressed by his consummate professionalism, erudition, and friendliness. I feel privileged to have known and worked with him.

Writing for *Analog* has also had the delightful fringe benefit of enabling me to meet and form friendships with other contributors to that magazine. A common characteristic among them is that they combine successful careers in science-related fields with great skill as writers. Among examples too numerous to mention here I will single out Edward M. Lerner, Nick Kanas, and Brad Aiken. Ed, with a strong background in physics and computer science, is equally adept at writing top-quality short fiction, novels, and nonfiction. Like

me, Nick and Brad have MD degrees and incorporate their own extensive medical experience into their works.

Next I would like to extend thanks and appreciation to my fellow members of the SIGMA science fiction think tank. Its membership includes the highest ranks of creative and productive science fiction writers, and it is an honor for me to be listed among the company of so many individuals whose writing accomplishments far exceed my own. Many of them responded to my request for what they considered good examples of medicine in science fiction and gave me excellent suggestions. Besides G. David Nordley, Stan Schmidt, and Ed Lerner, listing them in alphabetical order I am grateful for the help provided by Arlan Andrews, Sr. (the founder of SIGMA); Chris Christopher; Alan Dean Foster; Nancy Kress; Geoffrey A. Landis; Larry Niven; Jerry Pournelle; Allen Steele; and Bruce Sterling.

I am also grateful to Dr. Christian Caron, publishing editor for Springer's "Science and Fiction" series, for reviewing this book and providing me with helpful suggestions regarding it.

Finally, I wish to thank Dr. Robert Mayanovic, a professor and research physicist in the Department of Physics, Astronomy, and Materials Science at Missouri State University, for reviewing some of the calculations involving physics-related subjects I have included in this book. I am grateful to him for reassuring me that I correctly learned what he taught so well in the physics courses I have taken with him.

# Contents

<b>1</b>	<b>How the Human Body Works: From Quarks to Cells</b> . . . . .	<b>1</b>
1.1	The Stuff of Life. . . . .	2
1.2	What Is Life? . . . . .	6
1.3	The Chemistry of Life . . . . .	8
1.4	Cells and Their Contents . . . . .	13
1.4.1	Cytoplasm. . . . .	14
1.4.2	The Nucleus . . . . .	15
1.5	Human Anatomy . . . . .	18
1.5.1	Tissues. . . . .	19
1.5.2	Organs and Organ Systems . . . . .	20
1.6	The Bottom Line . . . . .	34
	References . . . . .	36
<b>2</b>	<b>Hurting and Healing Characters</b> . . . . .	<b>41</b>
2.1	Common Illnesses . . . . .	43
2.1.1	Common Causes of Death. . . . .	43
2.1.2	Cardiovascular Disease . . . . .	44
2.1.3	Infections . . . . .	47
2.1.4	Cancer. . . . .	51
2.1.5	Miscellaneous Health Issues . . . . .	53
2.2	Common Injuries . . . . .	54
2.2.1	Penetrating Injuries. . . . .	55
2.2.2	Blunt Trauma . . . . .	69
2.2.3	Burns. . . . .	71
2.2.4	Explosions. . . . .	73
2.2.5	Poisons and Toxins. . . . .	75
2.3	Delivering Medical Care . . . . .	76
2.4	"He's Dead, Jim." . . . .	82
2.5	The Bottom Line . . . . .	85
	References . . . . .	86
<b>3</b>	<b>Space Is a Dangerous Place</b> . . . . .	<b>89</b>
3.1	The Weakest Link . . . . .	91
3.2	Atmosphere and Pressure. . . . .	92
3.3	Temperature, Toxins, and Trauma . . . . .	99
3.4	Psychological Stress. . . . .	105

3.5	Circadian Rhythms and Sleep . . . . .	107
3.6	Risks of Meteoroids and Space Debris . . . . .	108
3.7	Acceleration and Deceleration . . . . .	113
3.8	The Bottom Line . . . . .	114
	References . . . . .	117
<b>4</b>	<b>Microgravity and the Human Body.</b> . . . .	<b>121</b>
4.1	Space Adaptation Syndrome . . . . .	122
4.2	Cardiovascular Effects . . . . .	125
4.3	Hematological Effects . . . . .	127
4.4	Musculoskeletal Effects . . . . .	128
4.5	Effects on Vision . . . . .	132
4.6	Gastrointestinal Effects . . . . .	133
4.7	Genitourinary and Endocrine Effects . . . . .	134
4.8	Pulmonary Effects . . . . .	135
4.9	Dealing with Microgravity . . . . .	135
4.10	The Bottom Line . . . . .	145
	References . . . . .	146
<b>5</b>	<b>Space Medicine: Paging Dr. McCoy.</b> . . . .	<b>151</b>
5.1	Medical Care in Space . . . . .	152
5.2	Preventive Care . . . . .	160
5.3	Exercise and Nutrition . . . . .	165
5.4	Infectious Diseases . . . . .	166
5.5	First Aid and Surgery in Space . . . . .	169
5.6	The Bottom Line . . . . .	178
	References . . . . .	184
<b>6</b>	<b>Danger! Radiation!</b> . . . . .	<b>187</b>
6.1	What is Radiation? . . . . .	188
6.2	Biological Effects of Radiation Exposure . . . . .	190
6.3	Radiation Dosage and the Human Body . . . . .	194
6.4	Realistic Settings for Radiation in Science Fiction . . . . .	197
6.5	Radiation in Space . . . . .	200
6.6	Protecting Against Radiation . . . . .	206
6.7	The Bottom Line . . . . .	207
	References . . . . .	208
<b>7</b>	<b>Suspended Animation: Putting Characters on Ice</b> . . . . .	<b>211</b>
7.1	Suspended Animation and Hibernation in Animals . . . . .	212
7.2	Suspended Animation and Humans . . . . .	214
7.3	How the Human Body Responds to Cold . . . . .	217
7.4	Therapeutic Hypothermia . . . . .	221
7.5	Cells and Cold . . . . .	230
7.6	Making Your Characters Chill Out . . . . .	232
7.7	Prospects for Reviving the Frozen . . . . .	236

7.8	Methods Equivalent to Suspended Animation . . . . .	239
7.9	The Bottom Line . . . . .	243
	References . . . . .	244
<b>8</b>	<b>Telepathy, Using the Force, and Other Paranormal Abilities . . . . .</b>	<b>249</b>
8.1	Telepathy . . . . .	250
8.2	Telekinesis . . . . .	259
8.3	Precognition . . . . .	264
8.4	Extrasensory Perception . . . . .	266
8.5	Teleportation . . . . .	270
8.6	The Bottom Line . . . . .	276
	References . . . . .	278
<b>9</b>	<b>The Biology of Immortality . . . . .</b>	<b>281</b>
9.1	The Dying of the Light . . . . .	283
9.2	Longevity and Genes . . . . .	287
9.3	Mechanisms and Theories of Aging . . . . .	292
9.4	The Quest for Eternal Youth . . . . .	297
9.5	The Hayflick and Other Limits . . . . .	302
9.6	The Future of Aging . . . . .	308
9.7	The Bottom Line . . . . .	310
	References . . . . .	314
<b>10</b>	<b>Sex in Science Fiction . . . . .</b>	<b>321</b>
10.1	Why Does Sex Exist? . . . . .	322
10.2	Technology and Sex . . . . .	328
10.3	Cloning . . . . .	332
10.4	Sex in Space . . . . .	335
10.5	Pregnancy in Space . . . . .	342
10.6	Space Kids . . . . .	349
10.7	Sex and Aliens . . . . .	351
10.8	The Bottom Line . . . . .	355
	References . . . . .	356
<b>11</b>	<b>The Promises and Perils of Medical Nanotechnology . . . . .</b>	<b>361</b>
11.1	Nanotechnology and the Human Body . . . . .	363
11.2	Medical Nanotechnology: The Dream . . . . .	364
11.3	Medical Nanotechnology: The Reality . . . . .	367
11.4	Risks of Medical Nanotechnology . . . . .	380
11.5	The Bottom Line . . . . .	383
	References . . . . .	385
<b>12</b>	<b>Genetic Engineering: Tinkering with the Human Body . . . . .</b>	<b>389</b>
12.1	Genes, Chromosomes, and Nature . . . . .	391
12.2	Potential Applications of Gene Therapy and Genetic Modification . . . . .	397

12.3	Current Status of Gene Therapy and Genetic Modification . . . . .	402
12.4	Genomic Medicine . . . . .	409
12.5	Repairing and Enhancing the Human Body . . . . .	413
12.6	Dangers of Genetic Engineering . . . . .	420
12.7	The Bottom Line . . . . .	423
	References . . . . .	424
<b>13</b>	<b>Stem Cells and Organ Transplantation: Resetting Our Biological Clocks. . . . .</b>	<b>429</b>
13.1	Types of Stem Cells . . . . .	430
13.2	Reprogramming Cells . . . . .	439
13.3	Risks of Stem Cells . . . . .	444
13.4	Organ Transplantation . . . . .	449
13.5	The Bottom Line . . . . .	458
	References . . . . .	461
<b>14</b>	<b>Bionics: Creating the Twenty-Four Million Dollar Man or Woman . . . . .</b>	<b>467</b>
14.1	Blending Machine and Flesh in Science Fiction . . . . .	468
14.2	How to Make a Cyborg . . . . .	469
14.3	Bionic Limbs . . . . .	470
14.4	The Bionic Eye . . . . .	477
14.5	The Bionic Ear . . . . .	482
14.6	Other "Bionic" Body Parts . . . . .	484
14.7	Connecting Brains to Computers and Machines . . . . .	487
14.8	Uploading Our Minds . . . . .	492
14.9	The Bottom Line . . . . .	499
	References . . . . .	502
<b>15</b>	<b>Summing Up: Using Medicine in Science Fiction. . . . .</b>	<b>507</b>
15.1	"As You Know, Bob..." . . . . .	508
15.2	Too Much or Too Little Medicine? . . . . .	510
15.3	Say or Suggest? . . . . .	513
15.4	The Limits of Extrapolation . . . . .	514
15.5	What Price Progress? . . . . .	524
15.6	The Bottom Line . . . . .	527
	<b>Appendix . . . . .</b>	<b>529</b>
	<b>Index . . . . .</b>	<b>537</b>

# 1

## How the Human Body Works: From Quarks to Cells

*What a piece of work is a man! How noble in reason! How infinite in faculty! In form, in moving, how express and admirable!*

William Shakespeare

*Hamlet*

*Man is the measure of all things.*

Protagoras

Science fiction is created by and for human beings. By definition it sets characters in times, places, and situations that subtly or overtly involve scientific principles. A science fiction work might take place in Earth's future, such as with the *Star Trek* universe. It may occur on worlds other than our own, as near as the Mars of Ray Bradbury's *The Martian Chronicles* stories or as remote as the intergalactic regions of E. E. "Doc" Smith's classic "Lensman" series. Or it could present science-based ideas and challenges in a contemporary (at least for a particular time) setting, like in early television series such as *Science Fiction Theatre* (1955–1957) or *The Outer Limits* (1963–1965). As a genre science fiction helps expand our conception of what reality is and humanity's place in the universe.

But however exotic the location or (perhaps literally) alien the individuals and groups depicted, how we understand and relate to what we read or see is inherently limited by our own minds and bodies. Even without consciously doing it we compare and contrast the scenes and "people" in a science fiction story, television show, or movie with our own experience and knowledge as individuals. Of necessity we use our own concepts of society and what it means to be human as the starting point for, if not necessarily judging, at least comprehending what is depicted in a science fiction work. In that sense, and updating the ancient Greek philosopher Protagoras, human beings truly are the measure of all things—at least to us human beings.

This intrinsic anthropic point of view also includes human biology. We use our own bodies and thought processes as the benchmark for understand-

ing the nonhuman. Here too this does not necessarily mean making value judgments about the superiority or inferiority of modern-day humans vis-à-vis other life forms, including versions of humanity altered from the current “norm” by scientific means or evolution. Instead it can be a simple matter-of-fact observation that most of the patrons at the Mos Eisley cantina in *Star Wars: A New Hope* (1977) have bodies noticeably different from ours. Likewise the fact that the extraterrestrial Kloros in Isaac Asimov’s short story “C-Chute” (1951) and some patients in James White’s “Sector General” series of works breathe chlorine rather than oxygen leads us to the inevitable conclusion that their physiology must be radically different from the human variety.

But to understand how our bodies would respond in new environments, the ways they can be injured or altered, and how they compare to possible nonhuman sentient beings such as extraterrestrials or machines with artificial intelligence, we must first understand what our bodies are and how they work. Each of us normally thinks of his or her body holistically, as a single entity encased by a boundary of flesh and operated by what a person considers “me.” While the literal truth of this basic “ghost in the machine” concept is an appropriate topic for philosophical and scientific critique, this is the way it typically *feels* to us when we stop to think about it and do not merely take what we “are” for granted.

However, just as a particular arrangement of metal, plastic, wheels, an engine, etc. can be conceptually lumped together into a single word, “automobile,” the term “human body” is our overall designation for a specific collection of many different materials and parts. The latter define what we are both physically and functionally, and they must continuously interact together in complex ways to sustain the process we call “life.” This chapter will examine what it is that, in the most fundamental sense, makes us what we are.

## 1.1 The Stuff of Life

Learning how the human body works involves studying it at different levels of size and complexity. We can figuratively peel away each of its layers like an onion or take it apart like a nested matryoshka doll. By going deep enough we leave the world of biology behind and enter that of physics, chemistry, and astronomy.

Like everything else in the universe our bodies are composed of matter and energy. Both of these terms are more complicated than one might think. We intuitively think of matter as the solid, liquid, or gaseous “stuff” that makes up the world. However, at a scale far smaller than our unaided senses can

detect, matter consists of “particles” called “atoms.” These occur singly or in combinations called “molecules” [1, 2].

Atoms in turn consist of still smaller “subatomic” particles that include protons, neutrons, and electrons. Protons have a single positive electrical charge, electrons have an equal but negative charge, and neutrons have no charge at all. Protons and neutrons in turn consist of combinations of even smaller particles called “quarks.” While protons and neutrons can exist independently of atoms, quarks are not seen in isolation.

An atom consists of a central “nucleus” surrounded by one or more “orbiting” electrons. This nucleus contains at least one proton and (usually) at least the same number (and often more) of neutrons. Nearly all the volume of an atom is empty space, with the nucleus and surrounding individual electrons being tiny compared to the atom’s overall size. Atoms with different number of protons are called “elements.” So far 118 elements have been identified, each with its own unique combination of chemical and other properties. Some of the most important elements involved in life processes include hydrogen (one proton), carbon (six protons), nitrogen (seven protons), and oxygen (eight protons).

“Isotopes” are atoms with the same number of protons but different number of neutrons. For example, the most common isotope of hydrogen has no neutrons, while another called “deuterium” has one neutron and a third, “tritium,” has two. Atoms normally have an equal number of protons and electrons. Since these latter particles have equal but opposite electric charges such an atom is electrically neutral, with no net charge. However, atoms can either gain electrons, thus producing a net negative charge, or lose electrons and develop a net positive charge. This process is called “ionization” and the charged atom is an “ion.”

The size and mass of an atom as well as its constituent parts are measured at scales far smaller than we normally use [3]. The size of a quark or electron is no more than about  $1 \times 10^{-18}$  m, and an electron has a mass of only about  $9.11 \times 10^{-31}$  kg. Protons and neutrons each have a size of about  $1 \times 10^{-15}$  m and similar masses—approximately  $1.67 \times 10^{-27}$  kg for a proton and minimally greater for a neutron. The average radius of the smallest type of atom, hydrogen, is on the order of  $5 \times 10^{-11}$  m.

A greatly oversimplified model of the atom compares it to our Solar System. The nucleus becomes analogous to our Sun and the orbiting electrons to planets. Some early twentieth century science fiction writers seized on this image and went one step further to postulate the existence of electrons really being subatomic worlds with plant, animal, and even human life similar to our Earth. This concept led to works like Ray Cummings’s novel *The Girl in the Golden Atom* (1922) and Henry Hasse’s novelette “He Who Shrank”

(1936). It also became a staple of comic book stories in the mid-twentieth century such as the Silver Age DC Comics superhero The Atom, whose ability to shrink as small as the plot required allowed him to visit these tiny worlds in stories such as “The World of the Magic Atom” (*The Atom* #19, June-July 1965) and “The Up and Down Dooms of the Atom” (*The Atom* #32, August-September 1967). Even his fellow Justice League of America colleagues Green Lantern and The Flash occasionally shrank down to meet friends and foes in thrill-packed adventures on subatomic planets, e.g. “Prisoner of the Power Ring” (*Green Lantern* #10, January 1962) and “Parasite Planet Peril” (*Green Lantern* #20, April 1963).

Unfortunately this idea has no basis in reality. An atomic nucleus with its protons and neutrons bound together is not analogous in its details to our Sun, which consists primarily of isolated protons and electrons, a much smaller proportion of helium nuclei (2 protons), and still tinier amounts of other ions in a high-temperature “plasma.” Electrons, protons, and neutrons may behave under some circumstances like discrete particles but as mathematically described waves under others. Far from having single orbits like planets the distances of electrons from the nucleus vary over a range of possible locations. The inhabitants of an electron-world would also presumably have to consist of “atoms” much smaller than the electron itself. For these and other reasons any story involving a subatomic world or even characters shrinking to or toward atomic size such as the 1957 movie *The Incredible Shrinking Man*, however thought-provoking in other ways, is not based on real science.

While we perceive matter as something tangible, energy is better described as a process, characterized by actual or potential action and change. Energy is defined in the most general terms as “the ability of one system to do work on another system” [4], or “the capacity to do work” [2]. Work is done when “energy is transferred to or from an object by means of a force acting on the object” [5].

These rather abstract concepts can be better understood by giving examples of the many forms of energy involved in life processes as well as others encountered in everyday life. “Kinetic” energy involves the motion of an object, such as a car moving down the street or the pedestrian walking on a nearby sidewalk. A compressed spring has “potential” energy—release the spring and the energy is converted to kinetic energy. The food we eat and digest releases “chemical” energy from interactions among the atoms and molecules in our meal. “Electrical” energy and “magnetic” energy are familiar to us regarding what they do based on our everyday experience with light bulbs and electronic devices or when we use a compass.

“Nuclear” energy is the kind stored within an atom’s nucleus itself and released under certain circumstances such as the explosion of an atomic bomb.

“Gravitational” energy includes the attraction that anything having mass exerts on other objects with mass and even “electromagnetic radiation” (e.g. light, see Chap. 6), which itself is a form of energy. “Thermal” energy involves motion at the atomic and molecular level and determines how “hot” or “cold” an object is, i.e. its temperature.

At the beginning of the twentieth century “classical” physics considered matter and energy to be distinct. Each was thought to be “conserved” in all interactions, that is, to be neither created nor destroyed. Several years later Albert Einstein postulated that matter could be converted into energy and vice versa, with the total amount of matter and energy in an interaction being conserved. This relationship is expressed quantitatively in his famous formula  $E=mc^2$ , where  $E$  is energy expressed in standard units of joules,  $m$  is the rest mass in kilograms, and  $c$  is the speed of light in a vacuum (slightly less than  $3 \times 10^8$  m/s).

Going back to the very beginning of time, all existing matter and energy originates from the “Big Bang” some 13.8 billion years ago when the universe itself started to expand from a tiny initial state with extremely high temperature and density [6–8]. What caused that expansion is still uncertain but we can be reasonably sure it was not due to a spaceship’s exploding fuel tank as suggested in the *Doctor Who* serial “Terminus” (1983). It ultimately resulted in the creation of two basic types of matter. Stars, planets, and us are all made of “baryonic” matter, the variety containing subatomic particles such as neutrons and protons that we consider “normal.” Only about 4.9% of the universe’s total matter and energy consists of baryonic matter [8].

Roughly 26.8% of the universe consists of “dark matter.” In this context the adjective “dark” does not refer to matter that has been seduced by the wrong side of the Force and joined the Sith. Instead this is matter that we can detect only by its gravitational effects, such as how huge amounts of it surrounding our Galaxy affect the latter’s rotation, and not by “seeing” it via light, radio waves, etc. Some dark matter may be baryonic and “dark” only due to our current inability to detect it due to its great distance or other factors. However, most is thought to be “non-baryonic,” consisting of theoretical particles whose exact nature is still uncertain. The remaining approximately 68.3% of the universe consists of “dark energy.” It is responsible for making the universe expand more rapidly than it otherwise would. What dark energy actually “is” remains uncertain, but it may be an intrinsic property of “empty” space itself.

The baryonic matter present in the early universe could not produce life as we know it. Shortly after its birth our cosmos consisted overwhelmingly (about 92% of nuclei) of a single element, hydrogen, with the remainder being helium except for an extremely tiny percentage of lithium (three protons

in its nucleus). During a period of several hundreds of millions of years after the Big Bang the first stars formed from that primordial hydrogen and later congregated into galaxies [7]. Stars significantly larger and more massive than our Sun ultimately explode as one type of “supernova.” For some time before and especially at the time of that explosion those stars produce elements more massive than hydrogen and helium, including the carbon, oxygen, etc. that we need for life. Those elements then become part of the huge hydrogen clouds that form “younger” stars like our Sun, born some 4.57 billion years ago, as well as the planets around those stars.

Thus, all the elements that make life on Earth (including human beings) possible are the “leftovers” from the creation of our Sun and the rest of the Solar System. While many elements have important roles to play in keeping us and other living things alive, the critical one is carbon. It has the most complex chemical interactions of any element, being able to form bonds with so many other types of atoms in so many different ways that it has an entire branch of chemistry devoted to it, “organic chemistry.” The common science fiction phrase “carbon-based life-form” does indeed describe us and every other living thing on Earth.

Besides carbon, the most common elements used by living things are hydrogen, oxygen, and nitrogen [9]. Other elements also have important roles to play. As we will see, sodium and potassium are critical for the functions of cells. Calcium and phosphorus are essential for bone development, and the latter also contributes to the types of molecules that generate the energy we need to live. Sulfur is a key component in other important molecules and iron is needed for production of our blood.

The single most important compound (defined as two or more elements chemically bonded in fixed proportions) [2] for terrestrial life is water. It consists of two hydrogen atoms bound with one of oxygen ( $H_2O$ ). Similar to carbon, in its liquid state water has both physical and chemical properties that allow a wide range of reactions among many different elements and compounds. Life on Earth originated due to the presence of large amounts of liquid water, and it makes up about 70% of an adult’s body weight.

## 1.2 What Is Life?

Water, carbon, and many other elements and compounds are the basic building blocks of terrestrial life at the atomic and molecular level. But even if we pour packets containing all the individual chemicals that make up our bodies into a large vat of water, no amount of stirring would make a person emerge from it. Not even someone as technologically advanced as Marvin the

Martian in the cartoon “Hare-Way to the Stars” (1958) could really create “just add water” Instant Martians. The ways that the raw, individually lifeless chemicals that make up a living thing are organized and interact are also crucial in deciding whether their combination constitutes life.

While it is easy to see that a rock is not alive<sup>1</sup> and a raccoon is, the exact boundary that separates the inorganic from the organic is fuzzy. Both past and present terrestrial life has taken an astonishing range of forms. Although both people and plants are living things, what “alive” means for each of them is, in terms of both chemistry and capability, very different.

Describing what extraterrestrial life might be like is a common practice in science fiction [10]. Those alien beings may to some degree be modeled on or at least inspired by various terrestrial forms of life in form and/or how they act. Thus, aliens may be humanoid and typically bipedal in appearance, as is generally the case in the *Star Trek* universe. In Larry Niven’s “Known Space” works the Kzinti are similar to felines, while Puppeteers are tripedal herbivores with a herd mentality, with the latter two traits shared by animals such as cattle and deer here on Earth. The Mesklinites of Hal Clement’s novel *Mission of Gravity* (1954) have centipede-like bodies as an adaptation to their high-gravity world, while the Selenites of H. G. Wells’s *The First Men in the Moon* (1901) are insectoid in appearance and have a society similar to an ant colony.

Aliens that differ markedly in appearance from anything terrestrial still may act in ways that humans can (although perhaps only with great effort) understand, often enough that some form of communication becomes possible with sentient extraterrestrials. Thus the titular character of Sir Fred Hoyle’s novel *The Black Cloud* (1957), though sharing little more than the fundamental laws of physics with us as living organisms, turns out to be relatively talkative. Even the otherwise incomprehensible radio wave-based Waveries in Fredric Brown’s story of that name (1945) show characteristics of being living such as moving volitionally, as do the unseen “aliens” of Robert A. Heinlein’s story “Goldfish Bowl” (1942).

The intrinsic properties and relative abundance in the universe of carbon and water compared to every element except hydrogen and helium make them successful materials for creating life—a statement whose proof can be found in your mirror. Science fiction occasionally deals with aliens who use elements other than carbon and water as the basis of their structure and life processes. For example, the chemical properties of silicon are in some ways similar to carbon, and under environmental conditions radically different than Earth’s (such as very high temperatures and/or pressures) might conceivably serve as

---

<sup>1</sup> Barring, of course, science fiction exceptions such as the *Outer Limits* episode “Corpus Earthling” (1963) or perhaps the Horta in the *Star Trek* episode “The Devil in the Dark” (1967).

a substitute. Even on our planet diatoms, a type of algae, protect themselves with walls made of silica (silicon dioxide).

Likewise liquid ammonia might be a reasonable replacement for water in organisms living at temperatures well below the latter's freezing point, although at the expense of slower chemical reactions. But overall the possibility of intelligent or even merely macroscopic life based on anything besides carbon and water remains speculative, with perhaps a slightly more optimistic possibility for microorganisms.

Given the myriad physical characteristics living things have or could have, defining what life is might be better approached indirectly by concentrating more on function than form—on what living beings do rather than merely how they are made. Traits associated with though not entirely defining life include having "...the capacity for growth, functional change, and continual change preceding death," [11] being "a self-sustaining chemical system capable of undergoing Darwinian evolution," [9], and the ability of living things to "take in energy from their surroundings and use it to maintain their structure and organization" [12].

The "Darwinian evolution" phrase includes the ideas that for a particular type of life to survive at least some of its kind must not only reproduce but create copies of themselves that are not quite identical in key ways from the "originals." Offspring having traits better adapted to living in a particular environment would thus be more likely to survive and reproduce than those that do not, in turn passing on those "adaptive" traits to their own offspring. This process is called "natural selection."

Still, even collectively such ideas cannot give a comprehensive or universal definition of life. In some ways the question goes beyond science and into the realm of philosophy [13]. Fortunately, after laying all this background, we can narrow our focus to the realm of the merely human type of life.

### 1.3 The Chemistry of Life

Although carbon and water form the core foundation for terrestrial life, including the human body, in themselves they are "inorganic." Neither a diamond nor the water in a glass would ever be considered living. However, certain chemicals consisting of carbon along with the two elements that form water, hydrogen and oxygen, and a few other elements such as sulfur and phosphorus form the biochemical infrastructure for our bodies. The four most important groups of chemicals used by terrestrial living organisms, including us, are carbohydrates, proteins, lipids, and nucleotides [14].

Carbohydrates consist of various combinations and arrangements of carbon, hydrogen, and oxygen atoms that in their simplest form have the formula  $(\text{CH}_2\text{O})_n$ —that is, a ratio of one carbon atom to two hydrogen atoms to one oxygen atom [15]. Simple carbohydrates such as glucose and fructose are “sugars” or, more technically, “monosaccharides.” Glucose is present in our blood and acts as an important energy source for our bodies. Fructose is the sugar that gives honey and many fruits their sweetness. Both glucose and fructose have identical formulas,  $\text{C}_6\text{H}_{12}\text{O}_6$ , but have different chemical properties because they are “isomers”—compounds with the same types and ratios of atoms but different structural or spatial arrangements of them.

Sucrose, or “table sugar,” is a “disaccharide”—a combination of one glucose molecule and one fructose molecule, with a formula of  $\text{C}_{12}\text{H}_{22}\text{O}_{11}$ . Lactose is found in the milk of nursing female mammals, including women, and is therefore called “milk sugar.” It has the same chemical formula as sucrose but is a combination of one glucose molecule with another sugar, galactose, with these latter two simple sugars also being isomers of each other. Disaccharides such as sucrose and lactose are broken down in our bodies into their constituent monosaccharides (e.g. glucose), which are then used as fuel for metabolic processes in our bodies—in other words, to produce energy for life.

A large number of monosaccharides also can link to each other to create a “polysaccharide,” a very long and chain-like molecule composed of many monosaccharide units. These “complex carbohydrates” include cellulose, glycogen, and starch. Cellulose is a major structural component in many plants, such as the wood of trees. Humans cannot digest the cellulose in the grains (e.g. bran) and vegetables we eat and thus use it for energy. However, the fibers and other forms of cellulose in those foods assist health by adding bulk to our stools (feces) and thus helping prevent constipation and other ills. Glycogen is a “storage” form of glucose present particularly in the liver and muscles. Plants use starches as an important energy source, and when we eat them in the form of potatoes and grains our bodies break them down into glucose molecules for our own fuel.

Proteins are critical to keeping us alive and, literally, in one piece. Without them our bodies would collapse into a watery and very dead mess. Some, such as collagen, give our bodies their structure, particularly within skin and bones. Enzymes are a large class of proteins that regulate our biochemical reactions. Proteins store some of the nutrients we need to live as well as transport substances (such as the oxygen in blood) to different areas of the body. Other varieties of proteins help form our muscles and make them work, while ones such as antibodies act to protect us from infections.

All proteins are assemblages of smaller units called “amino acids.” Our bodies use 20 different types of amino acids [15]. They all contain various com-

binations of carbon, hydrogen, and oxygen atoms, and some also include nitrogen and even sulfur. The human body can produce 10 of these amino acids on its own, but the other 10 must be obtained from food. Besides producing proteins, individual amino acids can be involved in creating other important body substances such as some neurotransmitters needed for our brains and nerves to function.

All but one of these 20 amino acids can exist in either of two forms that are mirror images of each other—a “right-handed” or “left-handed” form. All life on Earth uses the left-handed form exclusively. Thus, an astronaut marooned on a distant planet whose plants and animals used the right-handed variety could not use them to provide nutritional value as food. It is thought that life on our world does not use a combination of left- and right-handed amino acids because that would produce proteins and other substances that could not function properly.

Why terrestrial beings use only left-handed amino acids is speculative. It could be a random event, with life just happening to start with that variety instead of the right-handed one. Amino acids can actually form in the environment of space and may do so in originally equal amounts of the left- and right-handed types. Meteorites containing them may have fallen on the very young Earth and formed the building blocks for the ultimate development of life.

However, ultraviolet light produced by starlight in the region of space where the Sun formed might have selectively destroyed more right-handed amino acids than the left-handed variety due to how the light was “circularly polarized” [9]. The light waves in polarized light vibrate in only one direction, while those in unpolarized light vibrate in all directions perpendicular to the direction the light travels. Polarized light can also be oriented at different degrees relative to a circle surrounding the direction light is traveling. If the light is polarized in a particular way its energy will be more readily absorbed by one variety of “handed” amino acid than the other and destroy it, leaving the other type to predominate. Thus, it is at least plausible that life on planets orbiting stars similar to our Sun might also have been more likely to select left-handed amino acids too, and thus be potentially (assuming they do not contain other, poisonous substances) edible to us.

Like carbohydrates, lipids are composed of carbon, hydrogen, and oxygen atoms arranged in a variety of configurations. However, while many chemicals in the body need to be dissolved in water to react and keep us alive, lipids are at most poorly soluble in water. Among other things this property enables them to form “barriers” to areas where the body needs to prevent or regulate the passage of water. This includes the membranes of our cells, and

the “blood-brain barrier” that helps keep potentially harmful substances away from our brains.

Lipids include such classes as fatty acids, fats, oils, and steroids. Some types, such as phospholipids and glycolipids, have molecules with one end that is “hydrophilic” with a strong affinity for water along with a “hydrophobic” end that repels water. This characteristic allows them to interact in different ways with water simultaneously, both keeping water out of areas it should not go for a person to stay healthy and at the same time being able to have chemical and other interactions with it. For example, the phospholipids in a cell membrane help regulate how much water enters and leaves a cell. This “gate” function prevents too much water from either entering or leaking from a cell, either of which could make it not function properly or even destroy it.

Fats also serve as energy stores, such as in the form of adipose tissue—a type that some of us may have a bit more than we need. The human body uses glucose and other forms of carbohydrates as its main source of energy for routine metabolism, roughly comparably to how an automobile engine uses gasoline. During periods of increased exercise or other need such as environmental stress (e.g. being exposed to too much cold or heat) our bodies can, for a time, “step on the gas” by using greater amounts of carbohydrates to provide higher than baseline amounts of energy. Lipids act for the most part more as a long-term reserve fuel, used primarily to replenish other energy supplies as they are depleted.

Lipids also form the basis of triglycerides and cholesterol, two important chemicals that help transport fats through the body via the bloodstream. As we will see in the next chapter, too much of them in the blood can lead to serious problems, including blockage of blood vessels. However, having too little in the body would also be harmful. For example, cholesterol is part of cell membranes and needed to synthesize other important substances such as testosterone and estradiol, sex hormones that predominate in males and females respectively.

Water, carbohydrates, proteins, and lipids in various locations and combinations provide most of the raw material that comprise the human body. They are crucial to keeping it working as an efficient biological factory and doing the “grunt work” needed to keep us alive. But behind the scenes another class of chemicals common to all terrestrial life, nucleic acids, are working to make sure that our proteins are created as needed and made correctly so that they can regulate all the other substances within our bodies. The two primary types of nucleic acids, ribonucleic acid (RNA) and deoxyribonucleic acid (DNA), are required to produce all the cells in a human body [16]. DNA is also used as the “storage medium” for the instructions on how, under the proper circumstances, to make another human being. As we will see in later chapters,

changes in DNA and the characteristics of the particular set an individual inherits are critical for evolution and natural selection.

The molecules comprising more complex carbohydrates, proteins, and lipids are made of chains of smaller subunits, such as the various amino acids that make up proteins [17]. Nucleic acids are composed of three basic parts—a sugar molecule, a “base,” and a phosphate group (a phosphorous atom with four associated oxygen atoms)—linked in repeating units called “nucleotides.” RNA uses the sugar ribose in its nucleotide units while DNA uses deoxyribose. Phosphate groups attach to the sugar component to link the entire nucleotide sections together.

Both RNA and DNA use one of four different kinds of bases for each nucleotide unit. The three bases they have in common are adenine (A), cytosine (C), and guanine (G). They differ in which fourth base they use, with RNA employing uracil (U) and DNA thymine (T). Adenine and guanine are members of one class of chemicals, purines, while cytosine, thymine, and uracil belong to another, pyrimidines. *Gattaca* (1997), a science fiction movie dealing in essence with how “well” nucleic acids function within individuals, used the abbreviations (A, C, G, and T) that denote the sequence in which bases appear within a strand of DNA as part of its title—i.e. G (guanine) A (adenine) T (thymine) etc.

RNA molecules usually consist of a single strand of different nucleotide subunits. As Francis Crick and James Watson reported in 1953, DNA normally consists of two strands entwined together as part of a spiraling structure—the famous “double helix.” These paired strands are connected in a very specific, “complementary” way via their bases. Adenine in one strand couples only with thymine in DNA or uracil in RNA, while cytosine connects only to guanine. This property allows nucleic acids to code for the production of proteins.

In humans and other terrestrial life RNA and DNA are both involved in producing proteins. The information on how to construct a protein is included in a particular length of DNA based on the arrangements and types of bases in it. Making proteins involves production of “messenger RNA.” One strand of DNA, the template strand, directs creation of a single-stranded length of messenger RNA (mRNA) via a process called “transcription” [18, 19] The template DNA strand has a pattern of bases complementary to what will be incorporated into the mRNA—e.g. adenine and cytosine in the DNA will correspond to uracil and guanine respectively in the mRNA. The second or coding DNA strand and the mRNA have identical sequences of bases except that the DNA strand has thymine where uracil is located in the mRNA.

To make proteins, a section of the two strands comprising the DNA helix temporarily separate from each other. The mRNA is then formed using

the template DNA as a pattern for incorporating complementary bases into it, along with adding sugars and other needed components to complete the mRNA. A particular set and sequence of three nucleotides (a “triplet,” or “codon”) in the mRNA indicates which amino acid should be placed at a particular location to create a specific kind of protein.

A molecule called transfer RNA (tRNA) transports the amino acids needed to construct a protein to the mRNA. Each tRNA molecule is bound to a single amino acid. The tRNA in turn binds to the corresponding area on the mRNA that tells which amino acid should be put at a particular place in the future protein. The actual synthesis of the protein also involves ribosomal RNA (rRNA). In a process called “translation” the tRNA and rRNA combine their efforts to read the information in the mRNA and create a protein. The amino acids bound to tRNA are joined one after another in a sequential, linear fashion, like links in a chain, with the help of rRNA to eventually produce a complete protein.

## 1.4 Cells and Their Contents

The chemicals within our bodies are organized into two basic areas—cells and the “extracellular space” outside of cells [20]. All living organisms more complex than a virus consist of one cell or a collection of cells. Cells are self-contained in that they include all the components required to maintain their own life processes and replicate. A virus, while considered (at least nominally) living, cannot reproduce on its own but requires some of the machinery located within cells.

Single-celled organisms such as bacteria, protozoa, and some algae and fungi are “complete” in themselves. Each can independently interact with its environment by taking in nutrients, eliminating wastes, and reproducing. Some, such as cyanobacteria, form large colonies together consisting of many identical cells. Although life is thought to have originated on Earth perhaps as far back as 3.8 billion years ago, during most of that time it consisted of single-celled or very simple multicellular organisms. The emergence of a significant number of plants and creatures consisting of a more complicated collection of cells occurred during a period dating somewhere between only about 500 million to a billion years ago [21].

Complex, multicellular organisms such as humans are composed of different kinds of specialized cells. Each type contributes in its own way to the life processes of the whole body. One recent report estimated the total of cells in a 30-year old young adult weighing 70 kg (154 pounds) and 1.72 m (5 ft. 8 in.) tall as being at a minimum about  $3.72 \times 10^{13}$  (37.2 trillion) cells, with other

reported estimates reaching up to 10 quadrillion ( $1 \times 10^{16}$ ) [22]. Some of our cells move and work individually, such as red and white blood cells. Others are part of larger structures and function collectively, e.g. in whole organs like the liver and heart. The various types of cells differ from each other in size, shape, degree of mobility, and the specific biochemical processes that go on within them. However, all share some common traits and components.

### 1.4.1 Cytoplasm

The outer boundary of a cell is a thin layer called the cell membrane [23]. This membrane separates and protects the cell from its external environment and encloses its contents. In a figurative sense, the cell membrane acts as a cell's "skin." It regulates what goes in and out of the cell, allowing nutrients and life-sustaining substances to enter and waste products as well as ions, atoms, and molecules related to cell function to leave. Plants, fungi, and bacteria have a cell wall outside this membrane that provides additional protection and a more rigid structure. However, animal cells lack this wall, giving them more flexibility but at the cost of greater vulnerability.

The cell membrane also acts as a "bag" to hold the liquid cytoplasm, composed predominantly of water, inside it. The cytoplasm contains the cytoskeleton, a network of tiny filaments and tubules that helps provide and maintain a cell's shape. The cytoskeleton holds the cytoplasm's internal structures in place, is involved in managing movement of substances into, out of, and within the cell, and helps the cell move and grow. The cytoplasm also contains various concentrations of elements dissolved in it. For example, most of our body's potassium is contained within cells, while a greater concentration of sodium is normally outside them in the extracellular space.

The cytoplasm also contains "organelles"—specialized structures that carry out particular functions within the cell. The "endoplasmic reticulum" (ER) forms a network containing tiny tubes and sacs within the cytoplasm [24]. One type, the "rough" ER, helps process and transport proteins, while another, the "smooth" ER, helps create lipids and glucose. The Golgi apparatus is a relatively large organelle that prepares protein for use and transfers lipids to different parts of the cell [25].

Vacuoles and vesicles are tiny "bubbles" within the cytoplasm [26]. While vacuoles typically hold mainly water, vesicles can act as "storage containers" for lipids and other substances. Vesicles can also store materials within the cell for later excretion into the extracellular space and move proteins inside the cell. Lysosomes, a specialized kind of vesicle, contain enzymes that break down various waste products, help recycle damaged and worn out organelles, and destroy "foreign" (e.g. invading viruses and bacteria) materials within the

cell. Somewhat similar to a person's stomach, their contents are more acidic than the surrounding cytoplasm. The acid isolated inside lysosomes can “digest” food particles and other materials without damaging healthy parts of the cell.

Ribosomes contain rRNA [20]. They are the sites where proteins are constructed via the methods described previously. Ribosomes may be “free agents” moving within the cytoplasm, or they may be bound to membranes such as those found in the rough ER.

Mitochondria<sup>2</sup> are organelles that are critical for producing the energy our cells need to live [27]. They are the primary source for adenosine triphosphate (ATP), which acts like a molecular “battery” to transport chemical energy within a cell. Mitochondria produce ATP most efficiently via “oxidative phosphorylation,” a process that can include the breakdown of glucose into waste products of carbon dioxide and water. They are also the site of beta oxidation of fatty acids and other processes that produce ATP.

## 1.4.2 The Nucleus

The earliest forms of life on Earth were “prokaryotes,” a class that still exists today as bacteria and another kingdom of single-celled microorganisms called “Archaea.” Prokaryotic cells lack mitochondria and a true cytoskeleton. Their DNA is condensed into a “nucleoid” that is located within the cytoplasm but not separated from it by a membrane [20, 23, 28].

Plants, fungi, and animals (including us) are all “eukaryotes.” Our cells contain mitochondria and thus can produce more energy than a prokaryote can muster. Except for a small amount present in mitochondria, the DNA of eukaryotes is contained in a specialized structure, the nucleus. This organelle is separated from the cell's cytoplasm by a membrane system with two major components, an inner and outer nuclear membrane. Tiny pores in the nuclear membrane regulate passage of material between the nucleus and cytoplasm.

The shape of the nucleus is maintained via a system of filaments called the nucleoskeleton, somewhat analogous to what the cytoskeleton does for the rest of the cell. The nucleus itself also contains a specialized structure without a separate membrane called the nucleolus. It manufactures partially completed ribosomes that subsequently leave the nucleus for final assembly in the cytoplasm, where they play their essential role in creating proteins.

Most importantly, the nucleus and the DNA within it act as the command center for the cell by regulating the production of proteins. Single, coiled

---

<sup>2</sup> Not to be confused with the microscopic midi-chlorians mentioned by Qui-Gon Jinn in *Stars Wars: The Phantom Menace* (1999) as the intracellular “link” between macroscopic sentient life and the Force.

lengths of double-stranded DNA are bound to RNA and certain proteins, particularly a type called “histones,” to form “chromosomes.” [29, 30] Prokaryotes such as bacteria typically have a single large, circular chromosome. In humans and, as a rule, other eukaryotes chromosomes are linear structures. The DNA in chromosomes is coiled, compacted, and combined with certain proteins to make up a complex known as chromatin [31]. The net effect is that chromosomes are usually “balled up” within the chromatin and generally not seen as individual structures within the nucleus.

The number of chromosomes normally present in different species varies widely. A fruit fly has 8 chromosomes, a chicken 78, and one variety of butterfly has 268. Humans normally have 46 chromosomes. These include 22 different types of “autosomes,” each one designated by a number of 1 through 22. With a few important exceptions our cells are “diploid”—that is, they each contain a pair of each type of autosome, for a total of 44. The remaining two chromosomes needed to reach the usual total of 46 are sex chromosomes. These come in two varieties, an X chromosome and a Y chromosome. The presence of two X chromosomes (XX) in an individual’s cells produces a female, while the combination of one X chromosome and one Y chromosome produce a male (XY).

During cell division—“mitosis”—the chromosomes that are normally “lumped” together in the chromatin separate into individual strands [32]. Before a cell divides it produces a copy of each of its original chromosomes. When mitosis begins chromatin condenses into discrete chromosome pairs consisting of the original chromosome and its duplicate, joined together at a tiny area called the centromere. In animal cells, during mitosis the nucleolus disappears and the nuclear membrane breaks down. As the cell continues to divide each pair of chromosomes separates, so that when mitosis is complete each of the two “daughter” cells created has the same number and types of chromosomes as the original “parent” cell. After cell division is complete the nuclear membrane and a nucleolus reform in each of the two cells.

New cells produced by a different process, “meiosis,” [33] are “haploid.” Instead of the paired sets of chromosomes adding up to 46 that human diploid cells have, haploid cells contain only one set of 23 chromosomes. Gamete cells—oocytes and ova (immature and mature egg cells, respectively) in females and sperm cells in males—are haploid. They originate from a diploid cell containing two copies of each chromosome, one derived from the organism’s female parent and the other from its male one. This cell then divides into two new but different cells, each containing a single set of chromosomes whose patterns of DNA are a blend of parts derived from each of the organism’s parents. These two new cells then duplicate their chromosomes, with